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Published in:
Roomvent 2011

Publication date:
2011

Document Version
Peer reviewed version

AIRFLOW CHARACTERISTICS AT THE BREATHING ZONE OF A SEATED PERSON: INTERACTION OF THE FREE CONVECTION FLOW AND AN ASSISTING LOCALLY SUPPLIED FLOW FROM BELOW FOR PERSONALIZED VENTILATION APPLICATION

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Abstract

A workstation with Personalized Ventilation (PV) unit and a thermal manikin with realistic body and temperature distribution were set in a test room (4.70 m x 1.62 m x 2.6 m). Airflow at 15 L/s was supplied from a ceiling diffuser to ventilate the room and keep the temperature at 26 ^{o}C. The PV consisted of two plenum boxes nested in each other and placed below the desk top, with discharge slots 0.06 m x 0.5 m (W x L). The PV unit was pressed against the abdomen of the thermal manikin. Each box had a separate supply fan. The airflow supplied isothermally and upwards from the inner and outer box was the same: 4, 6, 8 and 10 L/s. The mean velocity field at the breathing zone was obtained by Particle Image Velocimetry: a dual cavity laser (λ = 532 nm) and two CCD cameras with 35 and 60 mm lenses. Seeding, glycerol droplets, was added to the total volume supply. The maximum absolute mean velocity measured near the mouth was 0.1 m/s, when the boxes were installed but not working. When the two slots supplied equal amount of air, the measured absolute mean velocity increased with increasing the supplied air with a maximum of 0.35 m/s at 10 L/s.

Keywords: confluent jets, personalized ventilation, airflow interaction, convection flow

Introduction

Research on personalized ventilation (PV) has been performed to improve the design for providing better inhaled air quality, perceived air quality, thermal comfort and personal protection from airborne pathogens (Melikov 2004, Kaczmarczyk et al., 2004, Cermak and Melikov 2006). Supplying clean personalised air from front by single circular free jet with a long potential core region has been shown to provide the best inhaled air quality by nozzles positioned at distance several initial diameters form the occupant's breathing zone (Melikov 2004). Advantage of the axisymmetric jet is that its performance with regard to inhaled air quality is independent on the positioning of the air supply nozzle relative to the human face: from top, left, right or from above (Melikov et al. 2007). In this case the PV jet is transverse to the upward free convection flow which exists around the human body. Target velocity of at least 0.25 m/s is needed for penetration of the free convection flow by the PV flow in order to provide improved inhaled air quality (Melikov 2004, Bolashikov et al. 2011). The performance of such PV units depends also on the airflow interaction with the boundary layer surrounding the occupant body. Thinning the boundary layer (control over the convection flow) is one way to improve the PV performance by supplying less PV air and achieving more clean air into the air inhaled by the occupant (Bolashikov et al. 2009a, Bolashikov et al. 2011, Melikov et al. 2011). Another way to control the airflow interaction is to affect directly the PV flow characteristics. The control over the PV jet is realised by changing the initial conditions and/or positioning of the PV supply jet relative to the occupant's body (Nielsen et al. 2007a, Nielsen 2007b, Khalifa et al. 2009).

PV jets discharging the clean air at the abdominal area upward to the breathing zone and thus assisting the free convection flow has also been reported (Melikov et al. 2002, 2003). The performance of such PV is limited to a maximum of 60% clean air supply to inhalation at flow rates exceeding 15 L/s. A way to affect the flow interaction and improve the performance of such PV system is by simply replacing the convection flow in front of the body with a PV jet by incorporating the PV diffuser into a plate tightly fitted to the abdomen of the occupant (Bolashikov et al. 2009a). Next to the clean air jet, at its outer surface (towards the room), additional jet (confluent jets) of recirculated room air is then generated with the same aerodynamic and thermal characteristics as the inner. This protects the inner PV jet from mixing with polluted room air and keeps it cleaner over a longer distance. The result is increased amount of clean air into the air inhaled resulting in better perceived air quality, health and protection for occupants from airborne diseases (Bolashikov et al. 2009b).

The present paper studies by Particle Image Velocimetry the airflow characteristics at the breathing zone when such system of two confluent jets supplying air upwards from the upper abdominal area is used.

Method

The experiment was performed in a full-scale test room with dimensions 4.70 m × 1.62 m × 2.60 m (W×L×H). Three ceiling-mounted light fixtures (6 W each) provided the background lighting. The test room itself was built in a laboratory hall, 0.7 m above the floor. The laboratory hall had a separate ventilation system allowing for temperature control and hence reduced heat transfer (the air temperature of the laboratory hall was kept at the same level as that of the test room itself).

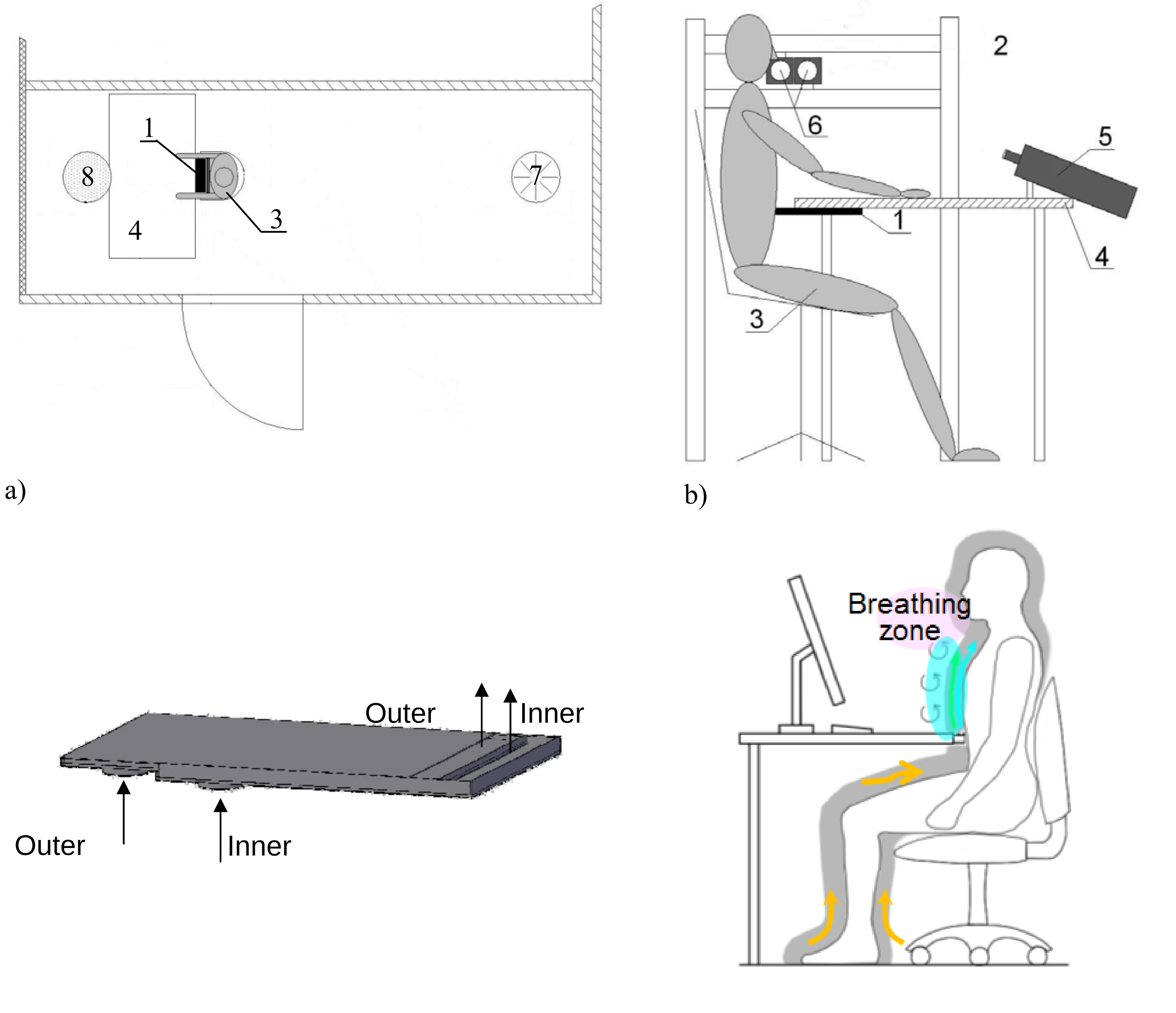
Mixing type of total volume (TV) ventilation was used to condition the air in the test room. The air supply diffuser (a circular swirl diffuser) and the air exhaust diffuser (a perforated circular diffuser) were installed on the ceiling (Figure 1a). The supplied air was 100% outdoor (no recirculation was used) with a flow rate of 15 L/s, which corresponded to an air change rate of 2.7 h^{-1}. A slight under-pressure of 1.4±0.1 Pa, resulting in 30 L/s at the exhaust, was kept during all the experimental conditions in order to avoid a flow of air from the test room to the surroundings and pollute with seeding the tall hall laboratory. The Air temperature in the test room as well as in the surroundings was kept 26 ^{o}C during all experimental conditions.

A workplace consisting of a desk with a seated breathing thermal manikin, an ordinary light office chair and personalized ventilation device that generated the personalized jet were used in the experimental set-up (Figure 1).

A breathing thermal manikin with body shape and size of an average Scandinavian woman 1.7 m in height was used to resemble a seated occupant. The surface temperature of the thermal manikin was controlled to be the same as the skin/clothing surface temperature of an average person in a state of thermal comfort at light sedentary activity and thus to realistically recreate the convective boundary layer existing around the body.

The air terminal device for the PV ventilation consisted of two plenum boxes (inner and outer box) nested in each other and placed below the desk top (Figure 1c). The two boxes had discharge slots with length of 0.5 m and width of 0.06 m. Each box had a separate fan to drive air through the slots. Thus the air supplied through the boxes generated two isothermal confluent jets. The two boxes were tightly attached so that the distance between the two generated air jets was always 0.004 m, i.e. almost no distance between the jets. The boxes were pressed firmly against the abdominal area of the thermal manikin (Figure 1d). When the box with the confluent jets was not installed and used the manikin was positioned 0.12 m backwards from the edge of the table (equal to the width of the two slots of the PV box with confluent jets).

The PIV equipment included a double cavity New Wave Solo 120XT Nd-YAG laser (wavelength 532 nm), capable of delivering light pulses of 120mJ. However the light pulses emitted were up to 60% of the maximal power. The pulse width, i.e. the duration of each illumination pulse, was 10 ns. The light sheet thickness at the measurement position was 2 mm. The laser was placed frontally, positioned to illuminate the face of the breathing thermal manikin from the front and along the axis bisecting the body in two symmetric halves. Two Dantec Dynamics Hi Sense MkII CCD cameras (1344×1024 pixels) equipped with 35 mm and 60 mm lenses and filters that only pass light with wavelengths close to that of the laser light were placed on the same side of the light sheet next to each other. In the present paper only the results for the 35 mm lenses camera are reported. The f-numbers (the focal length divided by the "effective" aperture diameter) were set to values between 4 and 5.6 to reduce the light budget of the particle scattering and reflections from the face of the breathing thermal manikin.



c) d)

Figure 1 PIV set-up of the experiment with the RMP a) chamber set-up and b) closer side view. 1) PV box with confluent jets, 2) camera stand, 3) thermal manikin, 4) table, 5) laser generator, 6) CCD cameras, 7) TV supply, 8) TV exhaust c) confluent jet design, d) application of confluent jets as PV unit.

The seeding used, consisting of glycerol droplets with a diameter of 2-3 μm, was added into the total volume ventilation supply. A particle generator was used to generate the particles from mixture of water and pure glycerol in volume parts 0.7 to 0.3. The particles were added more than 10 diameters before the TV supply plenum box, placed over the diffuser, in order to obtain a more homogeneous distribution of the tracers throughout the measurement chamber without significantly disturbing the flow pattern inside. Room air was supplied from the two PV boxes in order to achieve homogeneous seeding in both jets by use of two duct fans.

The images were processed using Dantec Flow Manager © software version 4.7. For each measurement position 1000 realizations were acquired. The recording of image maps was done with time between pulses and trigger rate dependent on the PV flow rate supplied by the RMP from 1 000 to 12 000 µs and from 0.2 to 2 Hz respectively. The largest time separation between pulses corresponds to the cases when only the convective flow was measured and the smallest ones to the case of PV at 10 L/s.

Reflections from the face of the breathing thermal manikin entering the CCD cameras constituted a problem for two reasons. The reflections appeared along the profile of the face in the part of the measurement region, corrupting the signal in this area. Unwanted reflections were suppressed by applying a paper tape strip over the reflecting surfaces covered with a mixture of Rhodamine 6G and black non-shiny paint. Rhodamine 6G is a fluorescent dye, absorbing light with the wavelength of the laser and reflecting light which has a wavelength slightly shifted from the absorbed one. Additionally, the cameras were equipped with green-pass filters, which only permitted the wavelengths of the laser to pass, allowing the scattering from the particles to pass unregistered.

Results

The results from the PIV measurements with the confluent jets are presented in Figure 2 in the form of vector plots of the average velocity within the x-y plane normal to the face and bisecting the manikin. Figure 3 shows the absolute mean velocity downstream the centre of the mouth opening within the same x-y measurement plane. The origin of the local Cartesian system is positioned at the geometrical centre of the manikin's mouth (Figure 2a). The absolute mean velocity within the x-y plane is given as:

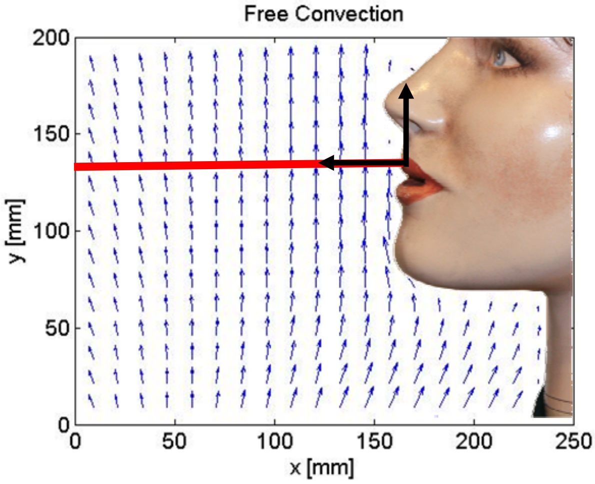
$$\overline{v} = \sqrt{\overline{v_x}^2 + \overline{v_y}^2}, \text{ where}$$

$\overline{v}$, mean absolute velocity value;
$\overline{v_x}$, the component of the mean velocity along the x axis;
$\overline{v_y}$, the component of the mean velocity along the y axis.

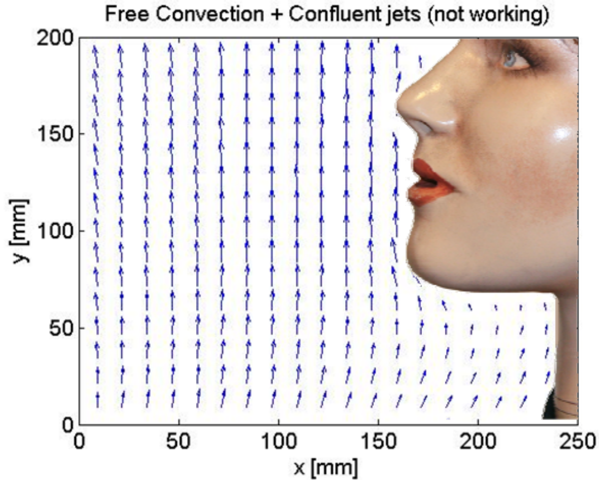
The placement of the PV confluent jet box tightly to the abdominal of the thermal manikin led to a weaker convection flow at the face compared to the case when there was the gap of 0.12 m between the manikin and the table (Figure 3). The weakening is noticed near the neck and the jaw (Figure 3b) where the convection flow is still not fully developed in the case when the confluent jets PV diffuser was used as an obstacle preventing the merging of the convection flow coming from the legs with that starting from the groins. The highest absolute velocity measured across the mouth of the seated manikin when the PV unit was not installed was 0.18 m/s at 26 ^{o}C room air temperature. When the PV unit was used to just block the air gap between the manikin's body and the table the absolute mean velocity magnitude decreased significantly to 0.11 m/s, nearly twice.

The air flow supplied from the two slots lead to an increase in the absolute mean velocity magnitude at the face of the thermal manikin. Across the mouth the velocity increased from 0.17 m/s at 4 L/s to 0.34 at 10 L/s (Figure 3b). It is noticed that when 6 or 8 or 10 L/s of PV air was supplied from each opening at the same time, there was a slight rise in the mean velocity 0.06 m away from the mouth: the width of the inner slot (Figure 3b). This can be explained with the interaction between the two confluent jets and proximity to the body surface. At 6, 8 and 10 L/s the upcoming inner jet spreads over the front of the manikin's body but when reaching the head level it is deflected by the chin. The presence of the outer jet prevented spreading of the inner jet outwards and kept it close to face (Figure 2d, 2e, 2f). At 8 L/s and 10 L/s less air hit the mandible and was deflected (Figures 2e, 2f). Due to its high initial momentum the jet spreads over the chest then splits in two streams and flows over the shoulders and away from the head (Lewis et al. 1967, Nagano private discussions 2009). At 4 L/s the initial momentum of the confluent jets was lower and they were deflected by the chin, thus affecting slightly the convection flow in front of the face. The maximum absolute mean velocity downstream from the mouth when the PV unit was supplying from both slots each at 4 L/s was 0.171 m/s and when the PV unit was not installed and the gap between the body and the table existed was 0.175 m/s (Figure 3b).

Breathing is a transient flow that needs to be considered when studying the flow interaction characteristics at the face of the occupants and its interaction with the PV flow and the convection layer surrounding the occupant's body. This however needs to be further investigated when used with the reported here confluent jet PV unit.



a)



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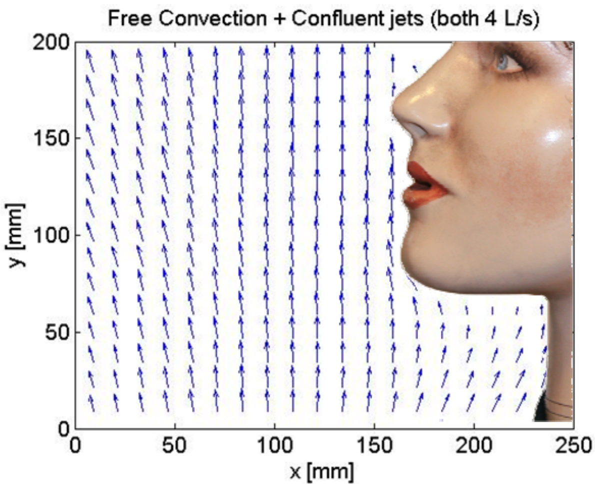

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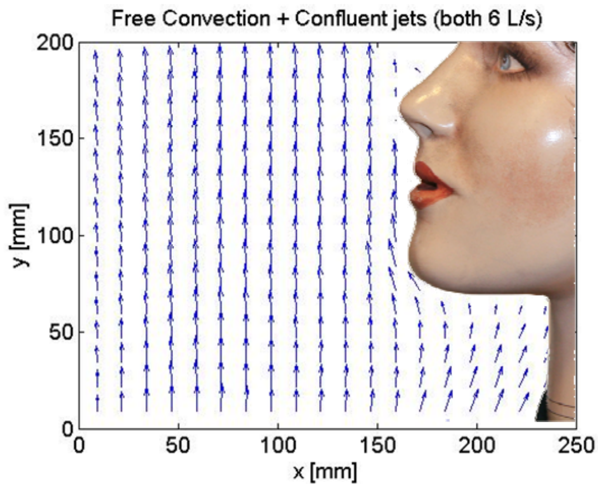

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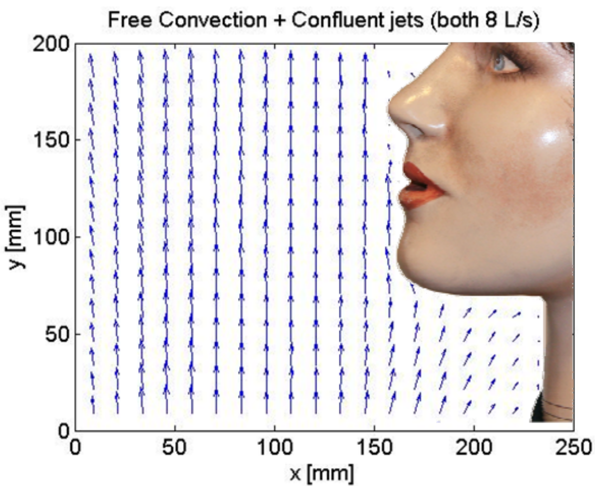

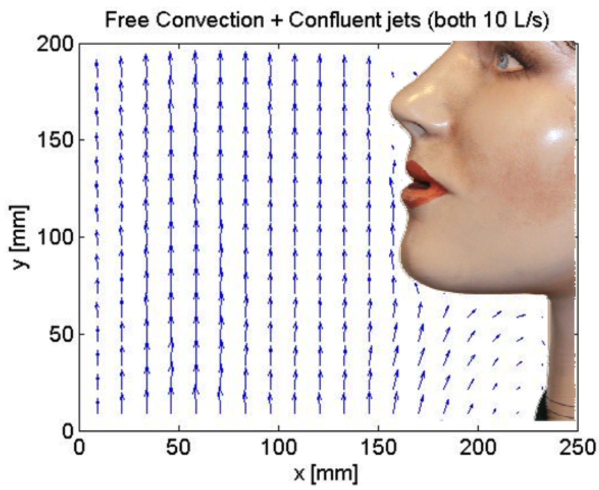

e) *f)*

Figure 2. Vector plots of velocity magnitude in the x, y plane bisecting the manikin measured with the PIV technique when a) there was 0.12 m air gap between the manikin and the table, b) the confluent jets PV was installed but not operational (used as obstacle), c) each slot of the confluent jets PV unit supplied upwards 4 L/s, d) each slot of the confluent jets PV unit supplied upwards 6 L/s, e) each slot of the confluent jets PV unit supplied upwards 8 L/s, f) each slot of the confluent jets PV unit supplied upwards 10 L/s.

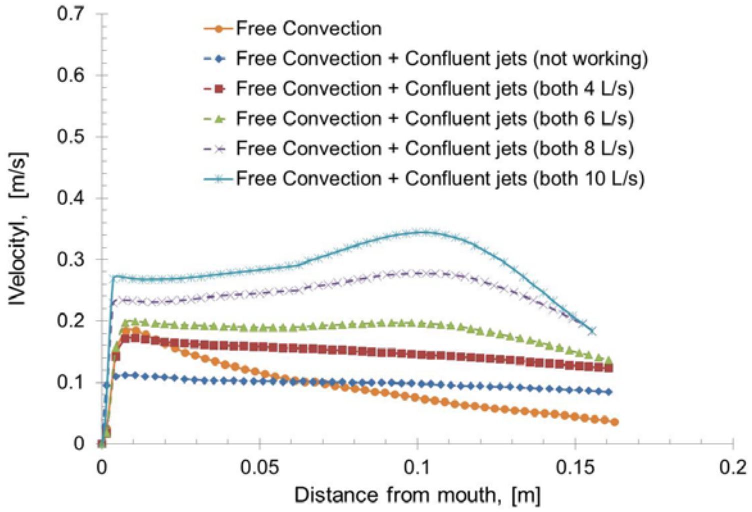

Figure 3. Absolute mean velocity magnitude presented along the middle section of the mouth for the 6 studied cases with and without the confluent jets PV unit operated at different supply flow rates.

Discussion

Instead of providing single jet of clean air towards the breathing zone, one can think of a way to provide some control over the PV flow in order to reduce its mixing with the surroundings. This can be realised by providing a jet of clean air upwards and tangentially to the body of the occupant from a thin slot positioned very close to the body at the upper abdominal area and having the length of the body width. In this way the head of the occupant would be immersed in the clean PV air jet. An additional, confluent jet of polluted room air with the same aerodynamic and thermal characteristics as the inner (closer to the body) PV jet can be supplied by a second slot opening to reduce the mixing between the surrounding room air and the clean PV air supplied by the inner jet. Thus the cleaner zone of the PV jet will be preserved for much longer distance on its way to the breathing zone of the occupant. This is demonstrated by the results reported in this paper.

The current study suggests that the body geometry is another important factor to be considered in the PV design especially for the cases when the PV air is supplied from below, tangentially to the front of occupant’s body. When discharged upwards the inner jet met the chin and was deflected away from the face. However, for flow rates above 6 L/s and for the current design, the outer confluent jet pushed the inner jet (will be clean air when used in practice) back towards the face. In this case the method of confluent jet PV may provide up to 85% personalized clean air into the air inhaled at 10 L/s (Bolashikov et al 2009b) compared to the design with a single PV jet giving only 60% clean air in inhalation at 20 L/s (Melikov et al. 2002). The reason for the poorer performance of the single jet design was the gap between the device and the breathing manikin’s body as well as the absence of protective secondary jet, allowing the upcoming boundary layer to dilute and mix more the clean PV air with the surrounding polluted room air. However further studies are required to justify the body shape effect on the performance of the PV unit by PIV measurements done in the plane parallel to the face, so that the separation of the upcoming flow by the chin can be clearly documented.

Bolashikov et al. (2011) and Melikov et al. (2011) showed that control over the flow interaction in front of the occupant when affecting the development of the convection flow is effective and the clean PV air when supplied from front reaches the breathing zone already at 4 L/s PV flow. The current study shows that the control over the flow interaction is quite dependent on the direction of the PV flow relative to the free convection, the body position and geometry. For PV flow supplied from front or sideways (transient) to the body and at the face, the amount of clean air ending up in the breathing zone depends mainly on the initial conditions of the PV flow (turbulence, velocity, discharge area) as well as the thickness of the boundary layer at the face. For assisting PV flow supplied from below (as reported in the present study), the body geometry becomes a factor of greatest significance: on its way upwards part of the air follows the convex structure of the jaws, while the remaining proceeds under the surface of the chin. Some of the air that overcomes the chin passes over the lips and becomes part of the air inhaled the rest flows along the cheeks, over the eyes, the forehead and joins the air that rises up from the sides and back of the head and the shoulders (forming the thermal plume above the person). This movement enhances the turbulence and hence the mixing of the PV flow with the surrounding room air resulting in the poor air quality performance of the confluent jets at flow rates below 10 L/s (Bolashikov et al. 2009b).

The advantage of the studied here strategy is that the confluent jet PV unit can be incorporated into a board installed below the desk top panel and pressed gently against the occupant's abdomen with a simple spring mechanism. Thus the two slots will not occupy useful space from the table and the discharge velocities will not disturb the work of the occupant. However elevated flow rates provided by the confluent PV jets unit can result in sensitisation and dryness feeling in the eyes. This however needs to be further studied in a set of human subject experiments.

Conclusion

Based on the performed measurements the following conclusions can be drawn:

- The convection layer surrounding the body of a seated occupant can develop velocities as high as 0.20 m/s at the facial area which are comparable with the recommended by the present standards upper limits for providing draught-free environment;
- When the two slots supplied equal amount of air, the measured absolute mean velocity increased with increasing the supplied air with maximum of 0.35 m/s at 10 L/s.
- For PV flow supplied from below the body geometry is an important factor that can adversely affect its performance with regards to providing clean air to the breathing zone;

Acknowledgements

This research was supported by the Danish Agency for Science Technology and Innovation. Project No. 09-064627.

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